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Review Article

The effects of ozone pretreatment on the physicochemical, functional, bioactive, textural, and sensory properties of medicinal plants: A comprehensive review

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Abstract

Background and aims: Ozone technology is utilized to inactivate enzymes, destroy microorganisms, and preserve and maintain food quality without chemicals as antimicrobial agents.

Methods: As an emerging processing technology, ozone pretreatment objectives combine some selected features with low molecular weight functional components and bioactive properties of medicinal plants. Changes observed were those in physical and functional properties such as pH, sensorial attributes of aroma and texture, and bioactive compounds like polyphenols, oxidants, and non-enzymatic enzymes.

Results: It has been shown through research that different reactions occur, which could be beneficial according to the mixture of plants present, given that each case has a different mechanism. Ozone's natural behavior, improved economic viability, and enhanced environmental safety distinguish it from traditional means. Nevertheless, research on the effects of ozone on functional and bioactive compounds of food and medicinal plants is still ongoing since it will be the basis for its establishment as a new technique.

Conclusion: The primary objectives achieved by applying ozone technology include maintaining and enhancing quality, improving antimicrobial efficiency, reducing chemical usage, environmental sustainability, and developing new processing methods. This study investigates the effect of ozone on the physical and functional properties, such as pH and sensory attributes, based on controlled experiments while analyzing the different reactions induced by ozone when combined with medicinal plants.

Keywords: Ozone, Medicinal plants, Natural products, Food processing

Introduction

Medicinal plants have been essential in traditional medicine disciplines since ancient times in curing and preventing various diseases. Many compounds found in such medicinal plants attract the attention of researchers and doctors based on their medicinal and therapeutic value. Active compounds in medicinal plants include alkaloids, flavonoids, terpenoids, polyphenols, tannins, and glycosides, each of which has significant biological effects that can help to improve human health. Scientists find these therapeutic effects to be therapeutic agents for the welfare of the people (1).

Alkaloids are crucial medicinal compounds in plants and have analgesic, anti-inflammatory, and anti-cancer characteristics. Flavonoids, found in ample quantity in colorful fruits and vegetables, are known for having antioxidant and anti-inflammatory characteristics capable of reducing the risk for cardiovascular disease and providing immune stimulation (2,3). In addition, terpenoids and polyphenols are other compounds found in active medicinal plants, which have antimicrobial, anti-inflammatory, and anti-cancer properties. For tannins, the tannins are used in the treatment of wounds and effects due to their astringent and antimicrobial properties. Glycosides are also found as compounds with different treatments in medicinal plants that can exist in various diseases (4).

The plants are then of medicinal value not only because of their effective phytochemical compounds but also in terms of environmental and economic use. Growing and using the plants medicinally might help decrease the chemical drugs used and act as a replenishable source for producing natural medications. In addition, using medicinal plants in traditional medicine is carried out by keeping essential indigenous and cultural knowledge (5). Hence, medicinal plants are a rich source of medicinal compounds exerting many different biological effects and are used to improve health and treat diseases. Further advanced research in this field could also guide toward the identification and development of new drugs from nature to have much more effective solutions for disease treatment.

Food and plant processing operations help improve or reduce active ingredients' nutritional value and activities but mostly retain them during storage. So far, heat treatment or heat sterilization has been the most popular method to protect these properties. However, it should be noted that food components are sensitive to extreme process parameters such as high temperature and may lead to the loss of pigments, vitamins, minerals, and antioxidants, eventually affecting their organoleptic properties and bioavailability (6).

In this regard, new processing methods that avoid applying direct heat to produce superior products without compromising nutrition and functional stability are gaining momentum (7). Non-thermal processing techniques are widespread in the study and have great potential, including high-pressure processing, pulsed electric field, pulsed light, ultrasonic processing, ozone processing, and non-thermal plasma. The existing research on the antimicrobial action of these technologies and their ability to bring about functional changes in food bears evidence of their potential for enhancing the quality and safety of food (8).

Ozone pretreatment is a novel non-thermal processing application in the food industry, and it is used as an option for traditional thermal preservation methods to retain the quality of foods. Ozone (O_3) is a reactive molecule that produces strong oxidation properties for microorganism destruction and enzyme inactivation. Due to these characteristics, ozone has been claimed to act as a powerful disinfecting agent in food processing (9).

Usually, an effective way of producing ozone is using a high-voltage electrical system or ultraviolet light. The molecule O_2 now becomes the powerful feedstock in processes called ozone (O_3(by which it can be utilized. As ozone possesses good disinfection properties, it may be helpful, for instance, to efficiently destroy microorganisms, viruses, and fungi (10).

Reactive intermediates developed in the ozonolysis process include free radicals such as the hydroxyl radical) OH•(and singlet oxygen)O2•(, hence inactivating microorganisms and degrading organic compounds. Such oxidation reactions may be found helpful in improving the shelf life and safety of food materials while removing deleterious compounds (11,12).

However, several issues are associated with the use of ozone in food processing. Because ozone is an unstable gas, it quickly degrades to molecular oxygen; thus, its generation and application must be done continuously. In addition, the level and duration of exposure to ozone must be strictly controlled to prevent the degradation of sensitive food components (13).

Generally, it is accepted that ozonation is a new non-thermal process with great potential in food quality and safety. More research in this area will always be necessary for process optimization and new application development for ozone in the food industry.

The advantages of ozone pretreatment are high antimicrobial efficiency, preservation of the quality of food, decrease in chemical concentration use, environmental friendliness, and shelf life. Ozone, which has a high oxidizing potential, can deactivate bacteria, viruses, and fungi and thus improve food safety and shelf life. Also, as a non-thermal method, it preserves heat-sensitive compounds of vitamins, pigments, and antioxidants that preserve food's nutritional value and sensory characteristics. As ozone replaces disinfectants and chemical preservatives, harmful chemicals in food processing are reduced along with environmental impacts. Some factors that tend to influence the use of ozone pretreatment are conditions of ozone concentration, contact time, type of food involved, conditions of processing, the delivery system of ozone, and safety considerations. The concentration and duration of contact must be appropriately adjusted and maintained so that the effectiveness of disinfection is applied as intended and the food quality is maintained. Environmental conditions such as humidity and temperature and the design of the system delivering ozone also influence the efficiency of ozone. Ozone is a very active and unstable gas that requires adequate manipulation and the proper use of corresponding protective equipment to avoid direct contact with personnel and eliminate respiration problems. These are crucial parameters when designing and implementing ozone pretreatment procedures and must be considered for excellent and safe results.

The use of ozone technology in the processing of medicinal plants is pursued with several goals, including preserving and improving the quality of medicinal plants, increasing antimicrobial efficiency, reducing the use of chemicals, improving environmental sustainability, and developing new processing methods. As a strong disinfectant, ozone can preserve the active compounds in medicinal plants and prevent their degradation, thereby maintaining their therapeutic and nutritional properties. Additionally, ozone helps reduce the microbial load and increase the shelf life of medicinal plants, which is crucial for storage purposes. Using ozone instead of chemical preservatives can minimize health and environmental risks and contribute to the production of high-quality and safe pharmaceutical and food products. Furthermore, ozone, as a non-thermal and environmentally friendly method, can mitigate the negative environmental impacts caused by chemicals and aid in preserving biodiversity and reducing pollution. Developing new and advanced processing methods using ozone can replace outdated and inefficient thermal methods, thus facilitating the production of high-quality, value-added products.

The necessity of research in this field is driven by the need to maintain active compounds, increase safety and health, reduce negative environmental effects, develop new methods, and improve the quality and efficiency of the products. Medicinal plants contain active compounds crucial for their therapeutic properties, and ozone, as a non-thermal method, can help preserve these compounds and prevent their degradation. Additionally, ozone can help reduce microbial load and extend the shelf life of products, thereby ensuring their safety and quality. Ozone, as a clean and environmentally friendly method, can help mitigate the adverse effects of chemical use. The need to develop new and efficient methods for processing medicinal plants is also apparent, and research in this field can address this need and aid in developing new and advanced techniques. Ozone can enhance the quality and efficiency of medicinal plant products, which is particularly important in producing high-quality, value-added products and can lead to greater consumer satisfaction. Given the goals mentioned earlier and necessities, research on using ozone technology to improve the quality and efficiency of medicinal plants is of paramount importance. It can lead to significant advancements in this field.

The effect of ozone on the main parts of medicinal plants

Plant medicinal species under ozone exposure can alter phenolic compounds, essential oils, nutrients, vitamin alkaloids, pigments, and cell structure. Changes in phenolic compounds by ozone can alter the medicinal effects because their antioxidant propriety, therapeutic effects, and free radical scavenger activities play a significant role. Also, it can alter the medicinal effects of essential oils because of changes in their composition and concentration and their antibacterial, antifungal, and antiviral properties. Medicinal plants contain vitamins and nutrients that are sensitive to oxidation; hence, ozone can lead to a loss in content and a change in the nutritional value of the plant. Besides, most plants also contain biologically active compounds such as alkaloids, which ozone can affect. This can modify the medicinal properties of the effect of the plant. Ozone also affects pigments found in medicinal plants, including anthocyanins and carotenoids. These pigments impact the appearance and quality of plants and their antioxidant properties. Conclusion: ozone causes the cells of medicinal plants to break their cellular structure, affecting their shelf life and the quality of the plant. All these effects will vary depending on the ozone concentration, exposure duration, and the medicinal plant variety. Knowing these effects gives an accurate understanding of how to use ozone in processing and preserving medicinal plants.

The effect of ozone on the physicochemical and functional properties of medicinal plants

The effects of ozone pretreatment on the performance of medicinal plants

Considering medicinal plants, ozone pretreatment drastically impacted plant performance due to changes in morphology, growth, metabolites, and the reproductive process. It has been observed that an increase in the level of ozone proved to radically reduce the growth parameters with severe leaf damage affecting the reproductive parts of the plants and altering the metabolite level when the *Sida cordifolia* L. plants were exposed to an elevation in ozone levels (14).

Similarly, research on *Costus pictus* D. Don plants showed reduced biomass, increased ROS accumulation, and changes in secondary metabolites under high ozone, affecting medicinal properties (15). Ozone treatment on plant biomass makes its decolorization improve cellulose accessibility and enzymatic bioconversion processes, where the degree of decolorization has been identified to enhance sugar yield (16). However, in general, changes in the growth pattern, metabolite levels, and biomass of medicinal plants are observed by ozone pretreatment, indicating that the effects of ozone on the yield and quality of medicinal plants should be considered (17).

pH and acidity

Ozone treatment has different effects on particular plant compounds ranging from sterile to in situ plants. The existing studies show conflicting observations concerning the impact of ozone on organic acids in various plant products. It is reported, for example, to increase the level of some organic acids in certain plants such as grapes, chicory, and tomatoes (18-20). Yet, with chlorogenic acid, caffeic acid, and cinnamic acid assistance, white wine, and kiwi are present in some plants, such as apple and grape juice (21).

It could be effective for improving vitamin C, an important antioxidant compound in medicinal plants, via the reaction of plant tissues to stress factors (21). Perhaps fruits and vegetables that have the highest levels related to this compound are more susceptible to contamination. Some previous studies demonstrated that ascorbic acid revealed no adverse effects in some green vegetable products like lettuce, spinach, and rocket leaves (22,23).

According to research (24), ozone pretreatment reduces the acidity and pH of medicinal plants while negatively affecting their strength, taste, aroma, and weight. In other research, ozone pretreatment has been reported to decrease the pH due to the release of organic acids. On the other hand, ozone reacts with lignin and does not affect the acidity of medicinal plants (25).

Being a strong oxidant, ozone destroys cell walls. It raises their permeability, thus releasing internal cell compounds and organic acids. Also, ozone can move the activity of enzymes related to the production of acids. All these processes can change in acidity and pH. Reducing pH raises product stability and decreases microbial growth.

As to the effect of ozone on the acidity of complex medicinal plants, there will be a difference depending on the plant species and specific organic acids contained in them, as well as the duration of treatment with it.

The effect of ozone gas on the amount of medicinal plant microbes

The research shows that ozone significantly reduces the microbial load of peppermint, summer savory, Iranian thyme, Indian valerian, etc. An ozone concentration of 0.9 ppm for 30 minutes significantly reduced the microbial load of medicinal plants. This survey and other research results show that using ozone as a disinfection method for medicinal plants is suitable (25,26).

Microbiological research on marjoram plants treated with ozone showed that ozone reduced the number of aerobic bacteria, yeasts, moulds, and mesophilic lactic acid bacteria. Fumigation of marjoram plants with gaseous ozone at a rate of 1 ppm caused a significant decrease in the number of aerobic yeast and mould colonies on the first and fifth days after treatment; this effect was attributed to the antibacterial activity of ozone, which is due to its strong oxidizing properties. Other studies have also shown the reduction of microbial stress in raw plant materials under the influence of ozone. For example, Piechowiak et al. used gaseous ozone at 8-10 ppm for 30 min every 12 hours to increase the storage life of raspberries at room temperature, and 48 h after treatment, a reduction of 1.18 log cfu g^{-1} in the total number of aerobic bacteria was observed. Turlock et al. found that ozone treatment for 120 min at concentrations of 2.8 and 5.3 mg/L in dry thyme produced significant reductions of 2.7 and 1.8 log in the number of aerobic colonies, respectively. Kazi et al also reported a 4-log decrease in aerobic bacteria in dry thyme and only 1-2 log in other plants after 30 or 60-minute ozone treatment at four ppm. Also, ozone treatment reduced the number of yeast and mould in marjoram plants. Guo et al reported a decrease in the number of aerobic mesophilic bacteria and fungi by 1.1 and 1.75 log cfu g^{-1}, respectively, in tomatoes stored under ozone treatment by 0.5 ± 4 ppm. Ozone treatment also reduced the number of mesophilic lactic acid bacteria below the detection threshold. In the research (27,28). Reducing the microbial load of medicinal plants and dealing with bacteria and pesticides with ozone pretreatment have been investigated.

That will be based on the research mentioned, where through different concentrations of ozone for a specific period, an enormous decrease can result in bacteria number, yeasts, and molds present in various medicinal plants like marjoram, Iranian thyme, mint, and so many others. This reduction is attributed to the fact that ozone has powerful antibacterial and antifungal properties, destroying microbial cell walls and damaging their internal structures, leading to the removal or reduction of their growth and multiplication (29). Therefore, the application of ozone as the method for disinfecting medicinal plants is quite proper and reasonable since it exerts a rather pronounced inhibitory action on the growth and multiplication of microorganisms and can reduce their microbial load to a significant extent.

Besides the direct destruction of cell walls and structures of microbes, ozone exerts its antimicrobial activity through several mechanisms, such as oxidation of lipids in the cell membrane, breaking some microbial components, disrupting microbial metabolism, and finally, forming free radicals that further increase oxidative stress. Besides, ozone induces DNA damage, which disrupts the reproduction and other activities of microbes. These mechanisms reflect a variety of antimicrobial actions, hence making ozone quite effective in different applications for disinfection.

The effect of ozone on the bioactive components of food

Polyphenols

Ozone pretreatment of medicinal plants significantly impacted the content of various parameters, which is responsible for increasing the chemical composition of bioactive compounds. Quite a few studies have been carried out on the effects of ozone treatment on plants, which recently showed that those have increased levels of polyphenols, vitamin C, and antioxidant potential in plants, as, for example, done with elderflower (30,31). Moreover, exposure to ozone increases the amount of ROS and the activity of enzymes responsible for the degradation of ROS, thereby contributing to the optimization of health status and minimization of oxidative damage in plants. Long-term exposure to high doses of ozone can activate negative processes of changes in the functions of plant cells, photosynthesis, and yield, which indicate the need for control in medicinal plant production. Also, the changes in the volatile organic compounds and changes in membrane integrity of plants are associated with exposure to ozone, providing evidence of the interactive relationship between ozone stress and the plant's chemistry (32).

The total polyphenol oxidase (PPO) activity the first day after the treatment in the plants that received ozone gas of 1 ppm for 1, 3, and 5 minutes significantly increased compared to the untreated sample. Activation of enzymes in the biosynthetic route of polyphenols and accumulation of reactive oxygen species during abiotic stress may be responsible. It was found by researchers (33) in 2017 that the periodic treatment with ozone in strawberries causes a rapid increase in the activity of phenylalanine ammonia-lyase, representing the first enzyme of the phenylpropanoid pathway, leading to the production of polyphenols. It has been demonstrated that gas disinfection causes an increment in plants' polyphenol content, and an increase in polyphenol content in plants after gas disinfection has been observed (34). Determining ozone dose during disinfection with one ppm could enhance the amounts of polyphenols in red-veined sorrel plants. Moreover, upon conversing with the rocket plant (*Eruca sativa* Mill.) using ozone at both 1 and 10 ppm levels for ten minutes, the material's polyphenol-like increased (35).

Antioxidants

Various methods have been used in analyzing antioxidants, including diphenyl-1-picrylhydrazyl (DPPH), ferric antioxidant reducing power (FRAP), oxygen radical absorbance capacity (ORAC), 2,2-azinobis diammonium salt, 3-ethylbenzothiazoline-6-sulfonic acid (ABTS) and tax equivalent antioxidant capacity (TEAC) which have shown a strong correlation (36). There is a consensus among many writers that ozone increases product antioxidant activity; however, others' findings show no change.

The antioxidant potential of marjoram plants significantly increased one day after the treatment when treated with gaseous ozone (1 ppm) as measured using the ABTS and DPPH methods, particularly for 3 min. For treatment durations exceeding five days, there was a continued elevation in antioxidant levels but only at periods of 7 or even 10 minutes.

The rise is associated with the entry of ozone through open pores and its combination with the calcium ion channels on the cell membrane, which results in massive generation of reactive oxygen species (anti-oxidative radicals) and antioxidant enzymes such as superoxide dismutase and peroxidases (35).

Other research studies have corroborated the above conclusions, indicating that ozone sensitivity levels differ significantly depending on plant species and treatment conditions. Red-veined sorrel plants, for instance, displayed conspicuous increments of antioxidants, particularly when subjected to a 10-minute ozone treatment time during the first day. Also, the experiment involved the effect of ozone treatment on *Kalanchoe daigremontiana* plants. The result of this study relates to an alternation that occurred in the concentration of the biological compounds. An increase in the concentration of the biological compounds was observed for one day in treatment for every dose of ozone that was subjected.

It can be inferred from the results that the samples treated with a 10 ppm ozone dosage for 1 minute showed the highest degree of antioxidant capacity, measured using ABTS and DPPH tests. In the ABTS test, 54% antioxidant capacity was recorded compared to control samples, representative of untreated alligator plants, and a close increase was also demonstrated through the DPPH test, amounting to approximately 65%. This likely led to an oxidative burst into the apoplast of the cells of the plants treated with ozone, caused by a redundant activation of the mechanisms of biosynthesis of low molecular weight antioxidants readily reacting with free radicals. Other researchers also report an increase in the antioxidant capacity of plant material under the influence of gaseous ozone. In other studies, decreases in antioxidant activity were observed in melon by Miller et al., pitaya fruit juice, and chili peppers receiving a high dose of ozone, which caused product catabolism, grated carrot, and parsley leaves. A few other studies found no effect of ozone treatment with concentrations up to 1 μmol/mol on the antioxidant activities. Overall, an increase in antioxidant activity appears to improve the health-promoting quality of the herbals (32,37-39).

Vitamins

Plant tissues responding to different stresses like ozone may affect their ability to regenerate vitamin C. Generally, non-green tissues contain smaller quantities of ascorbic acid than green tissues (40). Thus, fruits and green vegetables show more oxidation effects due to ozone treatment.

The rest was the fact that ozone treatment on alligator plants had an impact on the vitamin C content of the leaves. This value was variable and related to the concentration of ozone gas and the contact time of the alligator plant with its activity. Ozone treatment with a low concentration of 5 ppm, regardless of the duration of the process, led to a decrease in vitamin C content in leaves. It could be due to the activation of ascorbate oxidase, which degrades ascorbic acid.

Other researchers have also reported on the effect of ozonation on ascorbic acid content. In strawberries (41), researchers noted that during storage, the vitamin C content in fruits decreased primarily due to the oxidation of L-ascorbic acid to dehydroascorbic acid (42); however, this reduction was much lower in fruits treated with gaseous ozone.

Ascorbic acid can experience both oxidative and non-oxidative pathways of degradation. Such an acid is oxidized directly by the molecules of ozone or can be destroyed through the appearance of free radical intermediates. Nevertheless, the ultimate mechanism of degradation is through free radicals. Dehydroascorbic acid, a by-product of ascorbic acid oxidation, maintains its biological activity as a vitamin. It can regenerate ascorbic acid or become deeply oxidized to diketogulonic acid with no vitamin activity. Ascorbate oxidase is the enzyme responsible for converting ascorbic acid to dehydroascorbic acid. AOs are elevated in stress and result in ascorbic acid degradation. It is known how the elimination of free radicals formed under conditions of ozone decomposition diminishes the amount of ascorbic acid in fruit juice (43) and how the additional activation of ascorbate oxidase can serve to damage ascorbic acid in stress conditions (44,45).

This fact is explained by the authors, who noticed the positive effect of ozone on the level of vitamin C by maintaining its content because of the stimulation of the plant's natural defense mechanisms. This could be explained by increased synthesis and accumulation of antioxidant compounds, including ascorbic acid, in the cell to resist oxidative stress. Ozonized juices contained 68% more of this vitamin, while the pasteurized samples contained only 39% (46). Long-term storage reduces ascorbic acid content due to deteriorated fruit conditions (47).

The effect of ozone pretreatment on enzymes

Treatment with ozone can have a direct relationship with the antioxidant capacity and enzyme activity in the plant. O_3 increases the production of ROS in fruit cells and, therefore, increases the activity of enzymes with an antioxidant effect (48). PPO and peroxidase (POD) are the main enzymes responsible for oxidative stress. PPO catalyzes the hydroxylation of phenolic compounds in the hydroxyl group, which causes browning. POD is directly involved in ROS inactivation, ligninization, and ethylene biosynthesis; it also possesses antioxidant properties.

Furthermore, the enzyme activities show increased fruit and vegetable postharvest (49). The paramount role these enzymes play is to protect plants from oxidative stress and retard the aging process of fruits or vegetables. Besides, the influence of ozone on the activity of the enzyme defense reactions leads authors to categorically different outcomes. For example, an increase in POD and PPO activity was observed in pepper fruits. It is predominantly expressed under long-term ozone treatment (3 hours). In the carrot samples, a decrease in the activity of the same enzymes was revealed in comparison with the control samples after treatment with ozonized water (50). Applying an inappropriately long time with a high ozone concentration can induce an accumulation of ROS to increase the level of oxidative stress and, in the end, accelerate aging.

Changes in sensory properties with ozone pretreatment

Color

Color is one of the relevant distinguishing features of raw products that influence consumer choice. Such property results from the content of natural pigments like chlorophylls, carotenoids, anthocyanins, and other pigments formed during enzymatic and non-enzymatic reactions. Anthocyanins confer red color to strawberries, red berries, cherries, white grapes, and red-skinned apples. These pigments are also responsible for the antioxidant properties. Some studies revealed the involvement of ozone in the color of raw produce: for example, strawberry fruit samples that received ozonation treatment retained a better color owing to higher anthocyanin content. In the case of phenolic compounds, it has also been testified that ozonated water has a more significant advantage over its gaseous counterpart in terms of the retention of color (51).

The effect of ozone on the content of carotenoids is different in different studies; Some show positive effects, others show adverse effects, and some have failed to establish a relationship between ozone exposure and carotenoid levels. High concentrations and prolonged exposure to ozone may lead to a decrease in beta-carotene and lycopene content in fruits and vegetables, possibly through the oxidative cleavage of carotenoids, leading to the production of abscisic acid (ABA). However, the findings for chlorophyll pigments are slightly different; Most authors believe that ozone does not significantly alter chlorophyll levels (52).

It was noticed that ozone has a positive effect on preventing chlorophyll degradation during storage. Ozone can reduce the activity of chlorophyll-degrading enzymes such as chlorophyllase and chlorophyll-degrading peroxidase, which will lead to inhibiting the degradation of chlorophyll content (53).

Perfume and essential oil

The aromatic compounds in marjoram plants were also affected by ozone treatment. Thus, from the first day after the treatment, an increase in the content of a highly boiling monoterpenoid, sabinene, was observed, substantially affecting the quality of this plant's aroma. This was due to the direct activation of the plant's enzyme system (54). Linear monoterpenes result from precursors such as (IPP) and (DMAPP) and undergo a cycle of formation induced by ROS through free radical reactions. On the other hand, some oxygen derivatives, for example, 1-terpineol, were observed to decrease, which was attributed to the fact that the metabolism of hydrocarbons is limited in ozone-treated plants. Thus, five days after the treatment, no significant change in the composition of volatile compounds compared to treated and control plants was observed, which may indicate a return to biochemical balance before treatment. Therefore, marjoram plants treated with ozone should be subjected to processing or sale by the fifth day since, after this period, such plants lose their properties.

According to Vali Asill et al (55), ozone does not affect essential oil and gas, and interaction does not affect the essential oil content of plants. Pretreatment with ozone gas is suggested as a treatment method to improve and maintain the quality of plants and medicinal plants. The studies done in different articles show the positive effect of this method on the smell and essence of plants (56). Due to its strong detection properties, ozone gas can break down and remove organic compounds that produce unpleasant odors. This feature is especially true of the fresh and natural smell of the plant. In particular, ozone helps reduce unpleasant odors. It maintains a fresh and pleasant smell in fresh green produce and aromatic plants. Also, ozone treatment can change the aromatic compounds of plants. These changes include some aromatic compounds and the reduction of some undesirable compounds, which can improve the smell of plants and increase the olfactory attractiveness of the products. Regarding chemical composition, ozone gas can help maintain and increase the stability of helpful chemical compounds in plant essential oils.

These valuable features increase the useful life of products containing essential oils and maintain their quality over time (57). Some research shows that ozone can cause changes in the chemical composition of essential oils, which may include aromatic compounds and some other compounds. Although these changes can help improve crucial oils' aromatic and therapeutic properties, they require closer scrutiny to understand their precise messages. The compounds in the essential oils of medicinal plants play an important role in therapeutic properties, which can affect the therapeutic efficiency of essential oils. For example, increasing anti-inflammatory or antibacterial compounds can help boost anti-inflammatory drugs. They are using helpful life, such as increasing the stability and usefulness of herbal products, improving the sensory quality by reducing unpleasant and pleasant odors, and preserving therapeutic compounds. However, its use requires careful control of treatment conditions (e.g., time) to avoid unwanted degradation of beneficial compounds. Also, the changes made in the chemical composition of essential oils may continually improve and, in some cases, reduce the quality (49,58-61).

Conclusion

The present study has comprehensively reviewed the impacts of pretreatment with ozone on the physicochemical function and the bioactive, textural, and sensory characteristics of medicinal plants. From the results obtained in the present study, there is a high potential for ozone as a new, effective method of processing to improve and preserve the quality of medicinal plants. It can be said that one of the main findings of this study concerns the non-marked with positive effects of ozone in the compounds and aroma of volatile plants so that pretreatment with ozone led to increasing the concentration of some aromatic compounds like sabinene and reducing oxygen derivatives like 1-terpineol, in marjoram plants. The changes confirm that ozone can preserve and even enhance the plant's aroma, provided that they are used at most until the fifth day after the treatment because, after this period, the aromatic properties will start to decrease.

Also, ozone application stimulated ROS generation, thereby improving the activities of antioxidant enzymes such as PPO and POD. This issue, in turn, can help minimize oxidative damage and retain the quality of medicinal plants. More vitamin C is retained in fruit juices treated with ozone than in pasteurized samples. Although long-term storage decreases the content of ascorbic acid, in general, ozone is more effective in preserving nutrients.

Due to these strong oxidizing properties, ozone can be applied as a suitable and safe alternative to traditional processing methods. The advantages of its use are flexibility in application, cost-effectiveness, and improvement of environmental safety. This technology is developing due to the Await requirement of more research to understand the effects and optimization, and its wider adoption needs more research data. The results showed that pretreatment with ozone positively affects medicinal plants' sensory and texture characteristics. Color, aroma, and texture changes in medicinal plants are capable of enhancing consumer acceptance and also helping in the aspects of marketability. In this context, the present studies assume importance for improving postharvest quality and ensuring safety in medicinal plants and their value-added products.

The overall contribution of the study is to underline the enormous potential for ozone pretreatment as a contemporary processing technique in enhancing and maintaining quality for medicinal plants. Ozone either improves aromatic and bioactive compounds or increases the activity of antioxidant enzymes against oxidative damage. This technique shows better retention of nutrients, such as vitamin C, compared to traditional methods. Its benefits include flexibility, cost-effectiveness, and enhanced environmental safety. Although more studies are required to optimize and understand the complete applications of ozone treatment, it showed great promise in improving sensorial and textural quality, thus increasing medicinal plants' marketability and consumer acceptability. In this respect, ozone becomes one of the valuable tools for postharvest quality improvement and safety assurance of medicinal plants and their derived products.

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Competing Interests

The authors declare that there is no conflict of interest.

Ethical Approval

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